GPM for Cloud Microphysics Modeling

G. Tripoli[1], T. Hashino[1], W. Lewis[1], W-Y Leung[1], E.A. Smith[2] , A. Mugnai[3],

1 University of Wisconsin, Madison, Wisconsin
2 Goddard Space Flight Center – Greenbelt, Maryland
3 Institute of Atmospheric Sciences and Climate – Rome, Italy

The Future

- In the future, advances in computer technology will allow for **Cloud Resolving Weather Prediction Models** even on Global scales

The Uncertainty Principle for Weather

- Numerical weather prediction technology has never been and will never be able to escape the limitations of the nonlinearity of weather:
  - Overall predictability is driven by the energy containing disturbances
  - An energy-containing atmospheric disturbance is not predictable deterministically beyond one lifecycle (once nonlinearity sets in)

Examples of energy containing disturbances

• Long Wave disturbance	6-30 days
• Baroclinic wave	3-6 days
• Mesoscale Convective System	3-12 hours
• Cumulonimbus Plume	30-100 min
• Dry Thermal	3-10 min

The Weather Prediction Paradigm of the 20th Century Must Shift!

- Reject the expectation of deterministic analysis and prediction
- Embrace the reality of probabilistic analysis and prediction
- *We ought to estimate the spread of possible future outcomes irregardless of scale*

New Rules

- Probabilistic analyses would consist of
  - A dynamically and thermodynamically consistent set of state variables
    - Temperature, humidity
    - Wind
    - Liquid and ice microphysics
    - *Aerosols*
    - *Chemistry*
  - A spread of possible outcomes, as depicted by an ensemble
    - A narrow spread defines a deterministic outcome
    - A bimodal spread might suggest two quasi-equilibrium states, etc
  - Most likely outcome, perhaps represented by a mean of an ensemble
- A probabilistic forecast must consist of
  - Estimate of the spread of possible future states
  - Estimate of moist probable future state

GPM

- The GPM constellation will represent an indispensable source of information to potentially drive a *future* cloud resolving, global (or regional), **probabilistic analysis and prediction system.** GPM features**:**
  - **Unique** information that can potentially define microphysical structures
    - liquid
    - Ice
    - Precipitation rate
  - **Unique** information that implies the essence of fine scale circulations
    - Convective
      - Isolated
      - grouped
    - Stratiform
      - Embedded convection
      - Slantwise stability
- The Core satellite will effectively calibrate the constellation radiometers using probabilistic analysis techniques through the reduced uncertainty in its measurements, of microphysical structure (as will other possible observation systems when available).

GPM Research at MASL

(Mesoscale Atmospheric Simulation Laboratory)

- **AMPS** (Advanced Microphysics Prediction System)
  - SHIPS (Spectral Habit Ice Prediction System)
  - SLIPS (Spectral Liquid Prediction System)
  - SAPS (Spectral Aerosol Prediction System)
  - BSSS (Blowing Snow Simulation System)
- **CRSDAS** (Cloud Resolving Satellite Data Assimilation System)

Advanced Microphysics Prediction System (AMPS)

- The overarching goal is to take advantage of modern computing power **to bring 3D models of microphysics processes to the next level** in order to:
  - Realistically model the evolution and associated evolved structures of liquid and ice hydrometeors in complex cloud forms
  - Facilitate the realistic modeling of radiative transfer in cloudy air to better understand the relationship between satellite-observed brightness temperature and precipitation

Advanced Microphysics Prediction System (AMPS)

- Explicitly **evolve** characteristics of **shape, density, phase and size distribution** of **aerosol**, **liquid** and **ice** particles in a **3D** Eulerian framework.
- A basic research tool for understanding the microphysical processes and how they relate to microwave radiance observations
- A guide to defining how to develop simple, less resource-intensive microphysics schemes to be used in a probabilistic prediction system

Spectral Aerosol Prediction System

Aerosol categories (internally mixed)

CCN	**Partially soluble AP**	**Lognormal distribution**
IN	**Pure insoluble AP**	**Uniform distribution**

3 prognostic variables per a category

two moments of distribution

- mass content, ρ
- concentration, N

+

particle property variables (PPVs)

- aerosol mass content components
  aerosol soluble mass

• Currently the accumulation mode is modeled with the size distribution.

• This can be expanded to bin approach, or more size distributions can be added to describe nucleation mode and coarse mode as done by Wilson (2001).

Aerosol Microphysics

- **Nucleation scavenging and evaporation of hydrometeors are considered.**
- **Neither interaction among aerosols nor between aerosols and hydrometeors are considered**.

	CCN	IN
source	evaporation liquid hydrometeors solid hydrometeors	evaporation liquid hydrometeors solid hydrometeors
sink	nucleation scavenge impaction scavenge	nucleation scavenge deposition-condensation nuc. contact freezing nuc. impaction scavenge

Spectral Liquid Prediction System (SLiPS)

Liquid spectrum

4 prognostic variables per a bin

two moments of sub-distribution

- mass content, ρ
- concentration, N

+

particle property variables (PPVs)

- aerosol mass content components
  aerosol total mass
  aerosol soluble mass

- **About 20 bins seems to be optimal**
- **The vapor deposition is assumed to transfer mass of activated droplets into multiple bins to compensate the time step.**

Liquid microphysics

- CCN activation process
  - Kohler equation
- Vapor deposition process
  - Capacitance approach
- Collision-coalescence process
  - Quasi-stochastic model
- Collision-breakup process
  - Low and List (1982) formulation
- Aerosol mass prediction in the liquid hydrometeors
- Auto-Conversion….future work

Spectral Habit Ice Prediction System (SHIPS)

12 prognostic variables per a bin

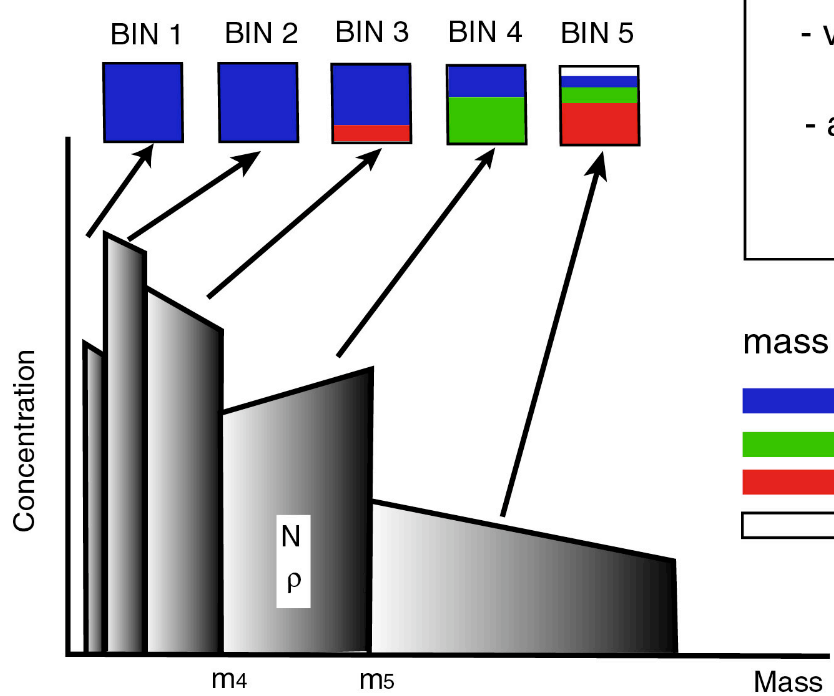
two moments of sub-distribution

- mass content, ρ
- concentration, N

+

particle property variables (PPVs)

- growth mass content components
  - ice crystal mass
  - rime mass
- lengths variable components
  - a-axis length
  - c-axis length
  - dendritic arm length
  - bullet rosette length
  - irregular crystal length
- volume variable components
  - circumscribing volume
- aerosol mass content components
  - aerosol total mass
  - aerosol soluble mass



mass content components

- ice crystal mass, m_I
- aggregate mass, m_A
- rime mass, m_R
- melt-water mass, m_W

PPVs

- Integrated based on local conditions and history of particles
- Each bin has different properties of ice particles.
- The properties change in time and space.

No use of categorization!

↕

Bin model
Bulk micro. par.

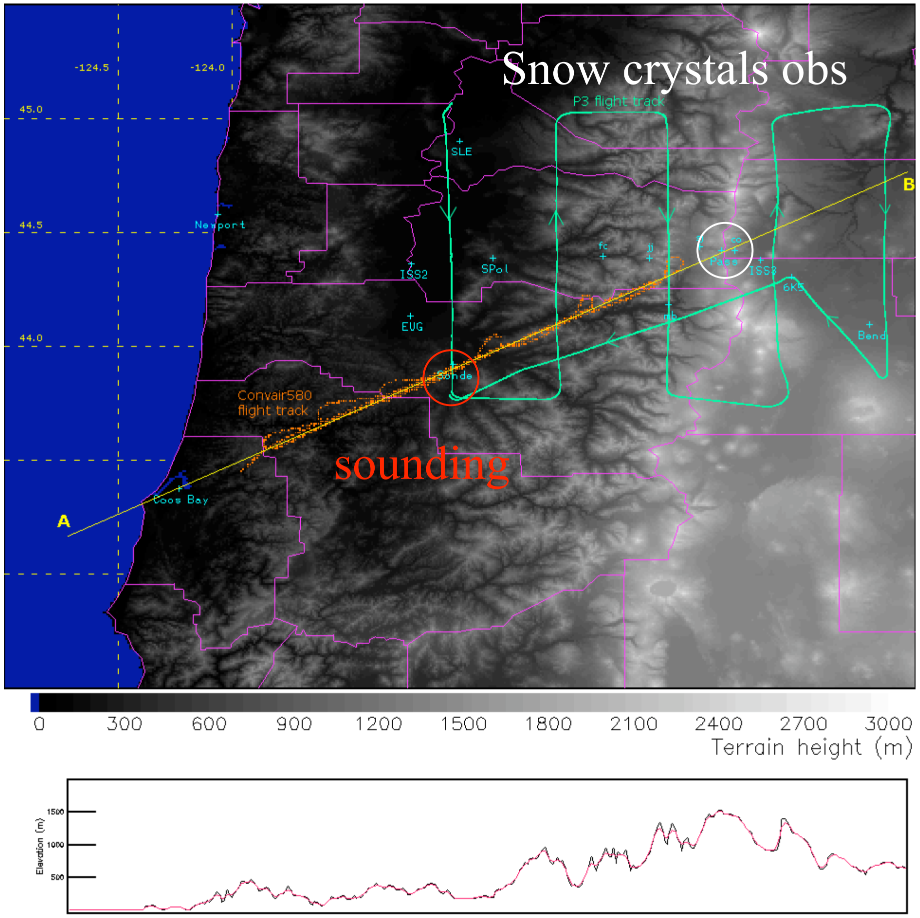
Outputs of SHIPS

- Concentration, mass content, and Particle Property Variables (PPVs) for a bin.
- Habit of ice crystals and type of solid hydrometeors in the bin can be diagnosed with PPVs.
- Predicted maximum dimension, circumscribing volume, aspect ratio, bulk density of solid hydrometeors.
- Aerosol distribution outside and inside hydrometeors, and solubility of the aerosols.

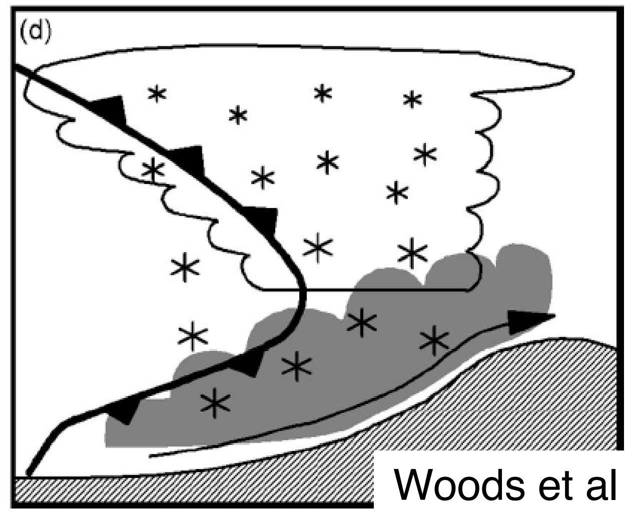
Ice microphysics

- Ice nucleation process
  - deposition-condensation nucleation, contact freezing, immersion freezing, secondary nucleation.
- Vapor deposition process
  - Capacitance analogy, empirical mass growth rate, probabilistic growth
- Collision-coalescence process
  - Quasi-stochastic approach for aggregation process and riming process
- Hydrodynamic breakup process
- Melting-shedding process
- Aerosol mass prediction in the solid hydrometeors

2D orographic snow storm simulation – IMPROVE-2 (13-14 Dec 2001)



From WMO Cloud Modeling Workshop (http://www.rap.ucar.edu/~gthompsn/workshop2004/)
IMPROVE 2 website (http://improve.atmos.washington.edu/)



Woods et al (2005)

Key microphysical processes for precipitation on the ground

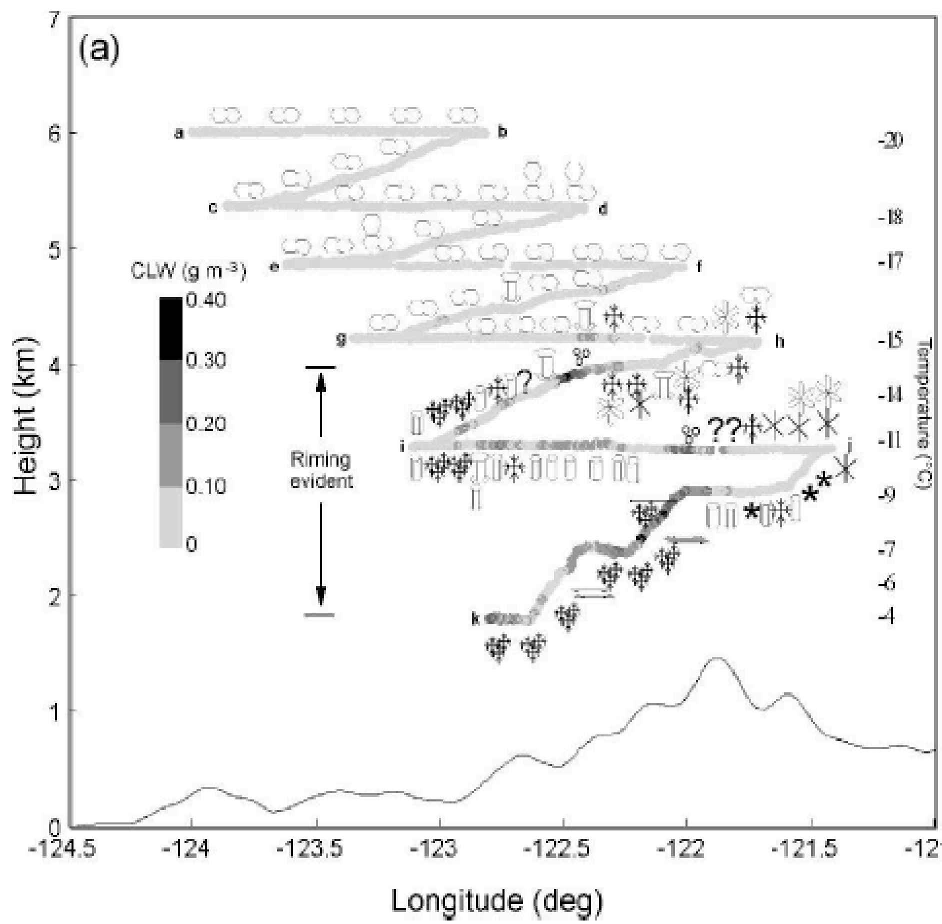
- Aggregation
- Riming

Habit dependent!

Observed ice particles

TABLE 3. Symbols and descriptions of crystal habits classified according to the scheme proposed by Magono and Lee (1966).

Symbol	Description
	Dendrite
	Stellar
*	Possible graupel-like snow
	Column
	Hexagonal plate
	Broad-branched crystal
	Crystal with sectorlike branches
	Sheath
	Needle
	Combination/bundle of needles
	Capped column
	Aggregates of dendrites
	Supercooled droplets and frozen droplets
	Assemblages of sectors, sideplanes, and plates, not dendrites.
?	Indeterminable type



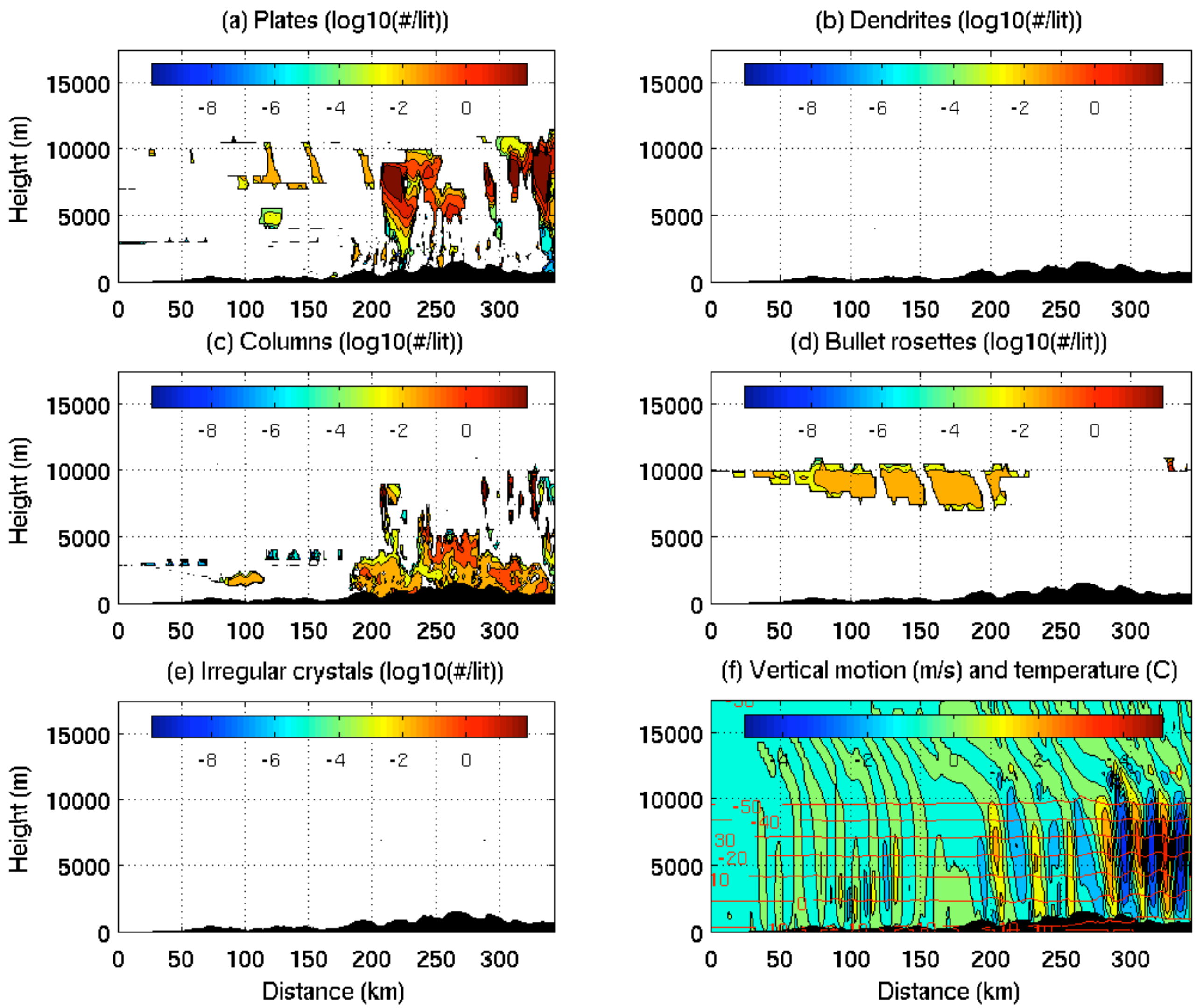
Woods et al. (2005)

Simulation with all processes

EXP1

Ice crystal habit of pristine and rimed crystals

12 hours of only liquid mic +
30 minutes vd and agg of ice mic +
1 hour of all the processes



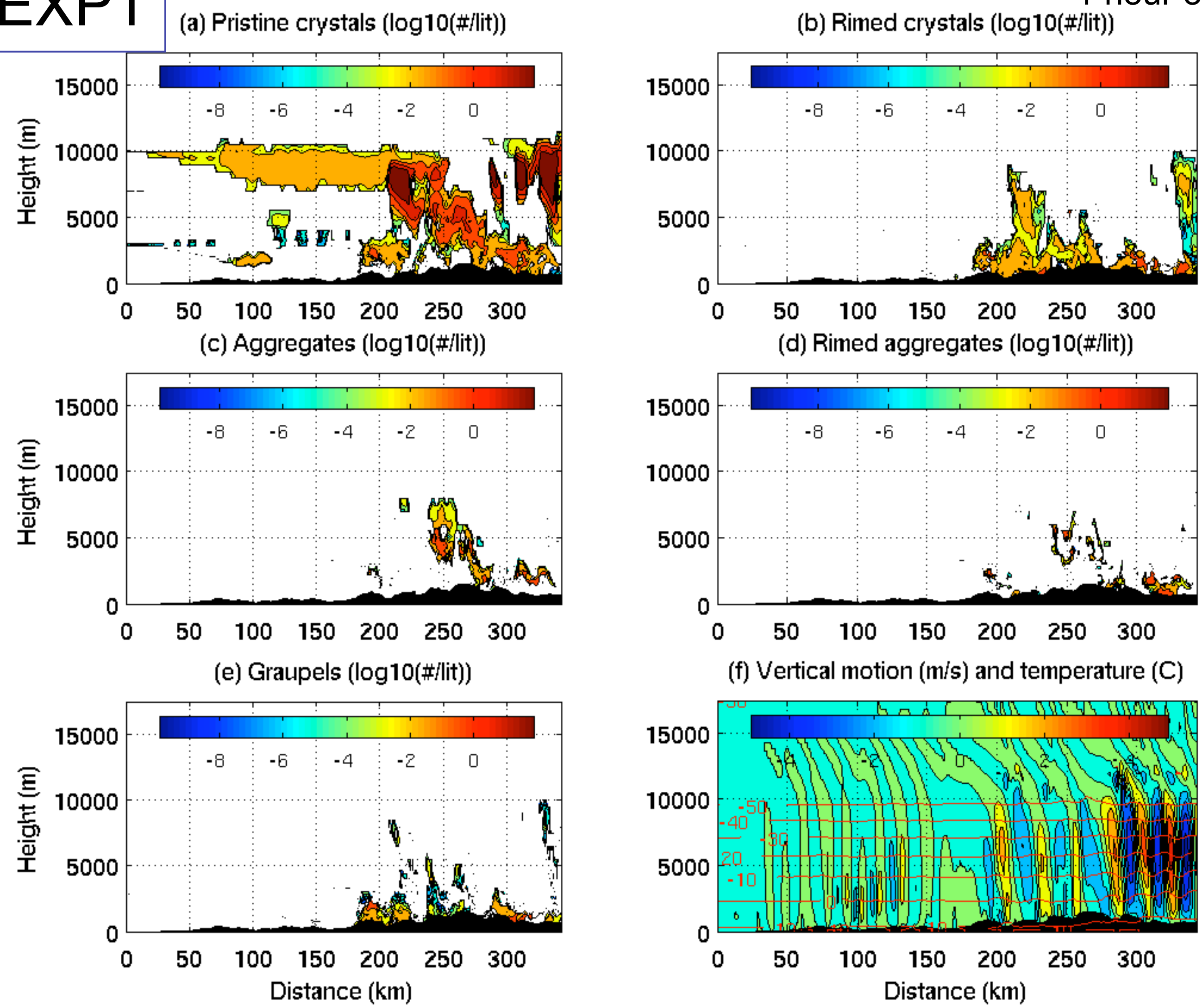
- Plates and columns are forming in high level due to immersion freezing.
- Bullet rosettes are forming in upper level and grow large due to less concentration.
- Columnar crystals dominates in lower levels.
- Dendrites were consumed by aggregation and riming before.

Simulation with all processes

Type of solid hydrometers

12 hours of only liquid mic +
30 minutes vd and agg of ice mic +
1 hour of all the processes

EXP1



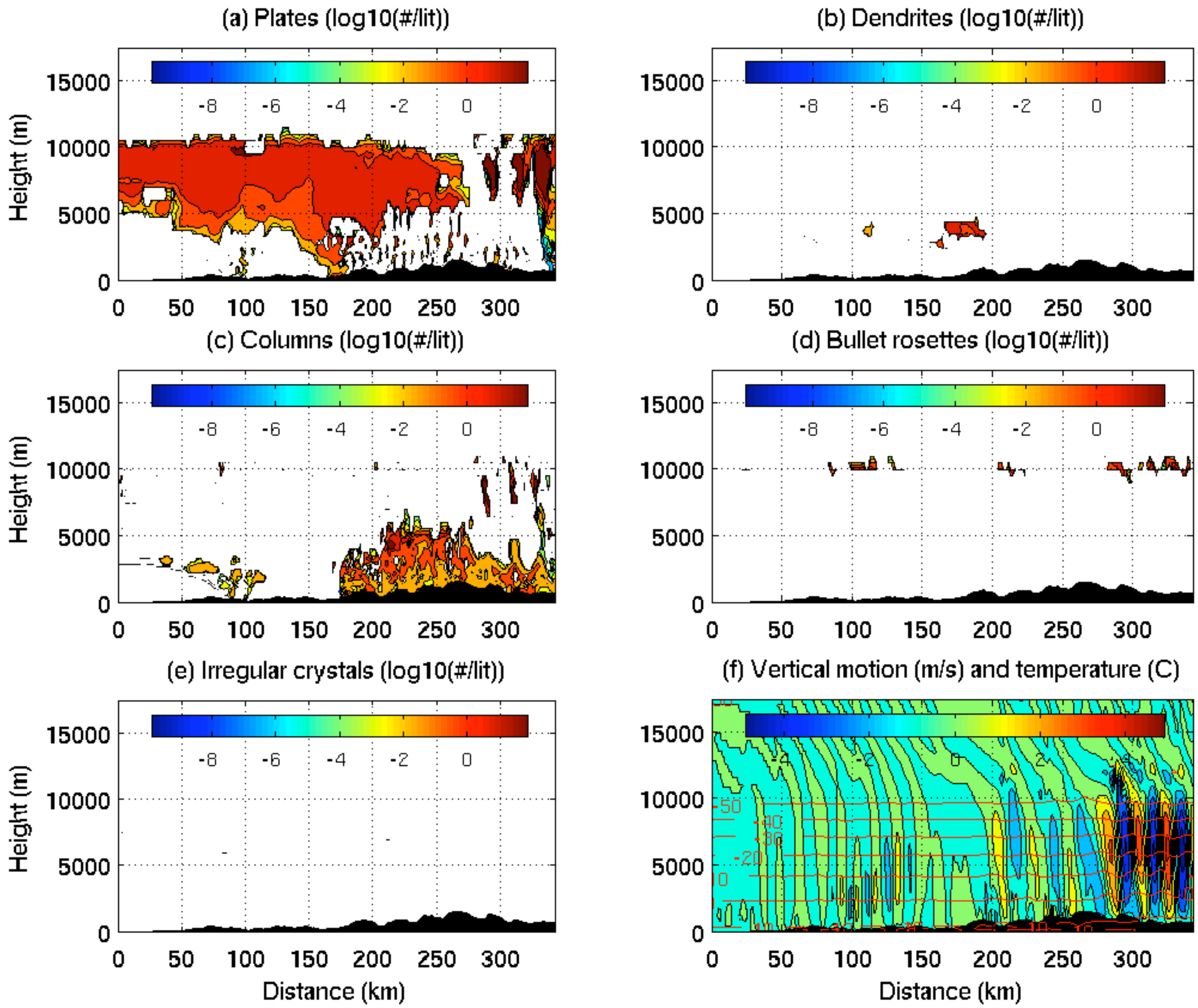
- Aggregates forming in higher level from bullet rosettes.
- Immersion process supplies crystals to the aggregation.
- Rimed crystals exist in high level due to small consumption by vapor deposition.

Simulation with all processes

UNI230

Ice crystal habit of pristine and rimed crystals

12 hours of only liquid mic +
30 minutes vd and agg of ice mic +
1 hour of all the processes



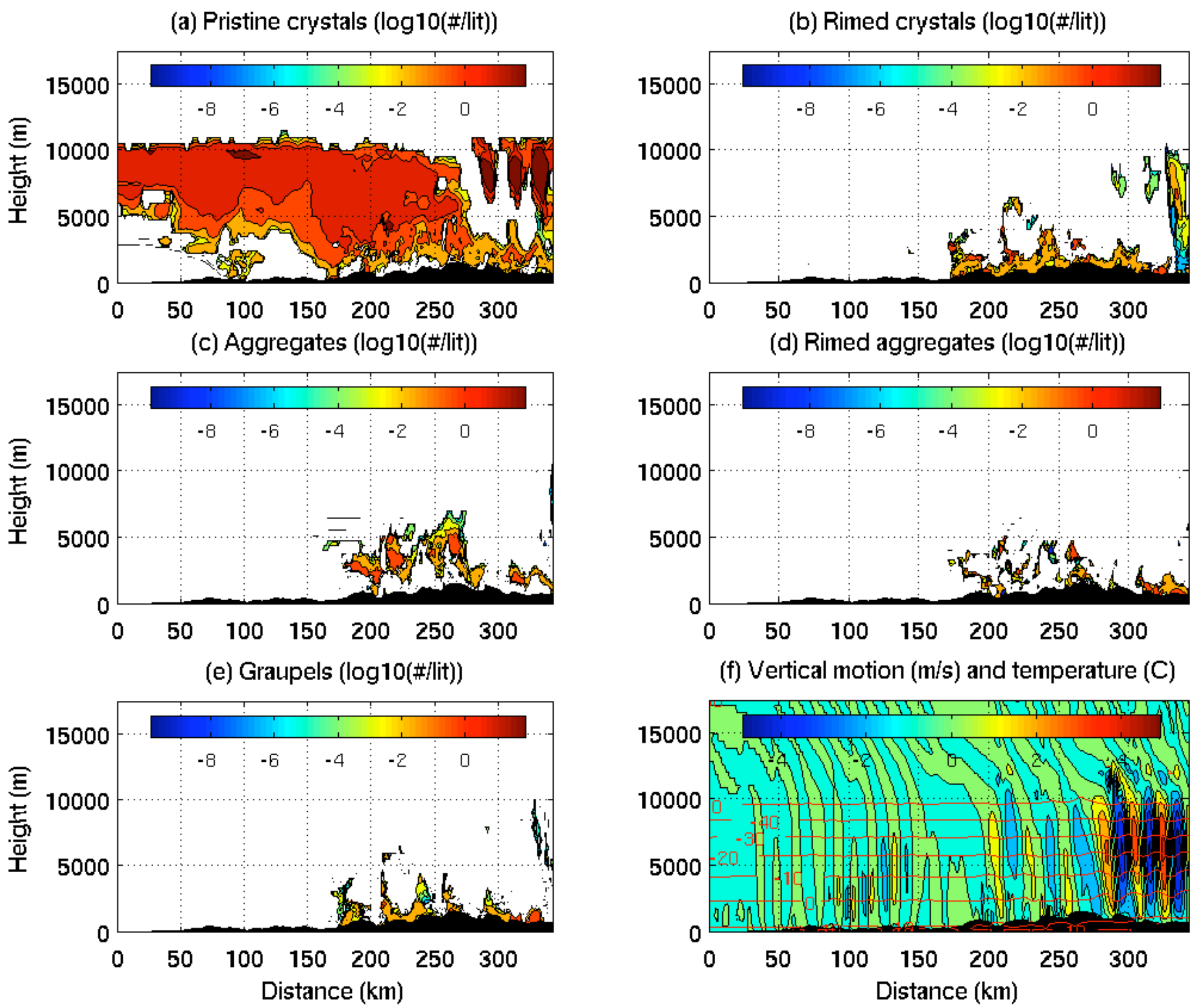
- Plates dominate in upper level due to vapor competition among high concentration of ice crystals.
- Dendrites form on plates falling from the above.
- Columnar crystals dominate in lower levels.
- Irregular crystals were only seen at very beginning of simulation.

Simulation with all processes

UNI230

Type of solid hydrometeors

12 hours of only liquid mic +
30 minutes vd and agg of ice mic +
1 hour of all the processes



- More aggregates at 3-5 km due to active formation by dendrites.
- Ice crystals are available for aggregation once the process starts.
- More active riming process in lower level
- The altitude of active riming corresponds to observation.

Some interesting results

- Importance of irregular polycrystals and bullet rossets to growth process
- Interaction of different sizes and chemical species of aerosols in determining predominant habits and process
- Sensitivity of roles of relative roles of immersion freezing and depositional nucleation to aerosol budget

Radiative Transfer Modeling of AMPS by Mugnai

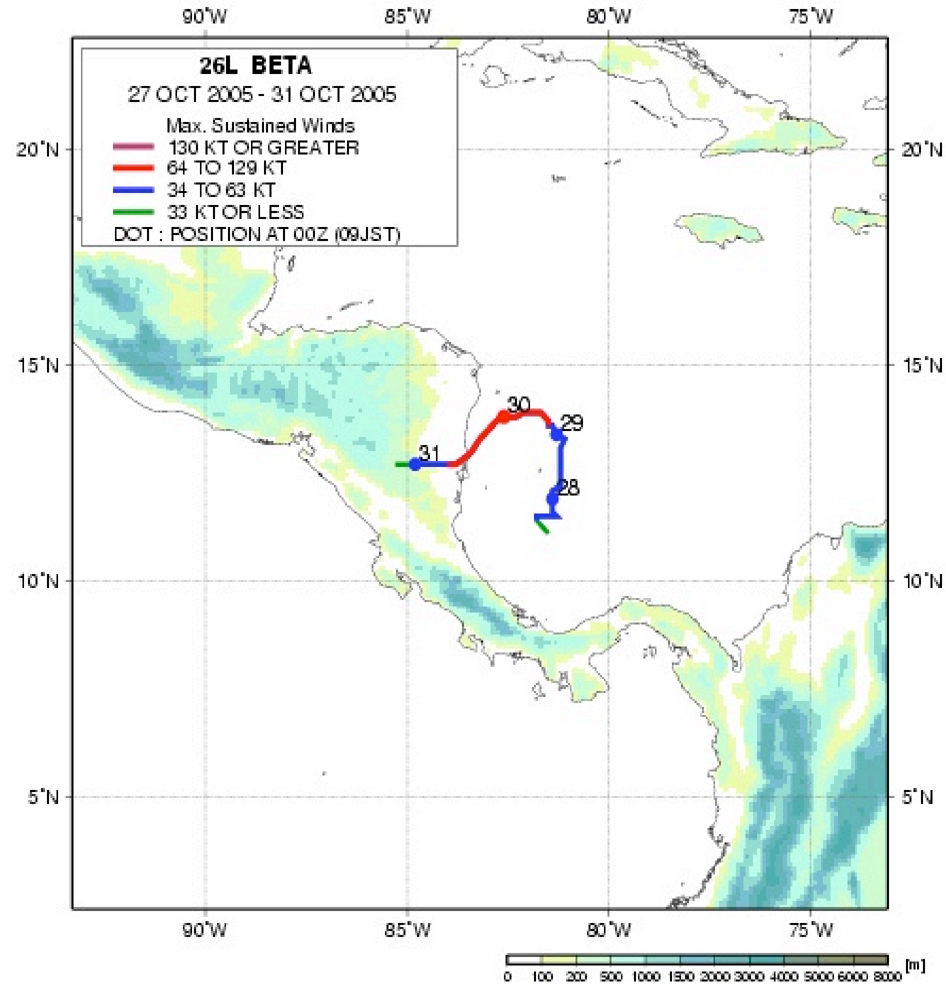
- Calculate radiative transfer from explicit microphysics
  - Explicit size bins
  - Structure characteristics of each bin defined
    - Progress from simple treatment to more complex treatment
      - Spheres
      - Equivalent spheres
      - Complex shapes
  - Multiple phase of each bin

Cloud Resolving Satellite Data Assimilation System CRSDAS

- Based on OSSE work for a hypothetical Nexrad Radar In Geostationary Orbit (with Will Lewis, Eastwoord Im, Eric Smith)
- Ensemble Kahlman Filter
- Assumed 15 minute reflectivity and Doppler velocity data
- Applied (so far) to limited area simulation of
  - Supercell
  - Hurricane Genesis

Hurricane Beta

- Fairly typical October hurricane: western Caribbean genesis
- Entire life cycle in 5 x 5 grid box: eliminates the necessity for moving grids.
- Maximum intensity: 962 hPa, 100knots.
- Primary impacts in Nicaragua: moderate storm surge inundation, extensive freshwater flooding.
- Typical of the kind of tropical cyclone for which NIS could provide valuable surveillance.



OSSE Methodology

• Produce a “Truth” simulation (TR).

• The satellite subpoint is set at _ = -82.5°.

• Synthetic observations are computed from TR at each gridpoint where the simulated reflectivity meets or exceeds 5 dBZ.

• Instrument-observed radial velocity is computed according to:

$$V_R = (v_T – w) \cos\_ \cos\_ + u \cos\_ \sin\_ + v \sin\_ \cos\_,$$

where _ = _ +__ and _ = _ + __; and _, _ are the scan angles in the N/S and E/W directions respectively.

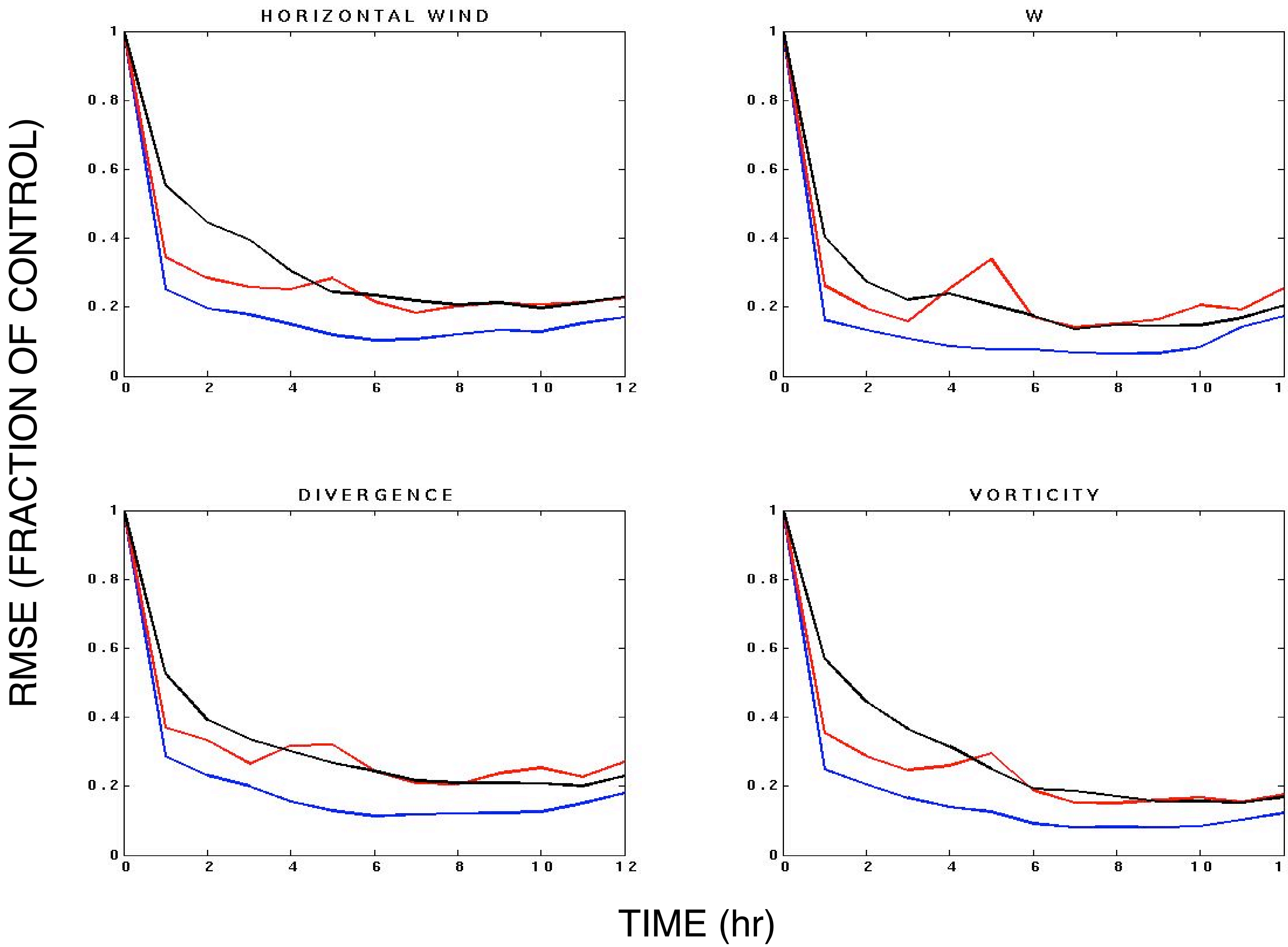
• Initialize an ensemble, use the EnKF to assimilate the observations of V_R and Z, and assess the impact.

Model Info and Configuration

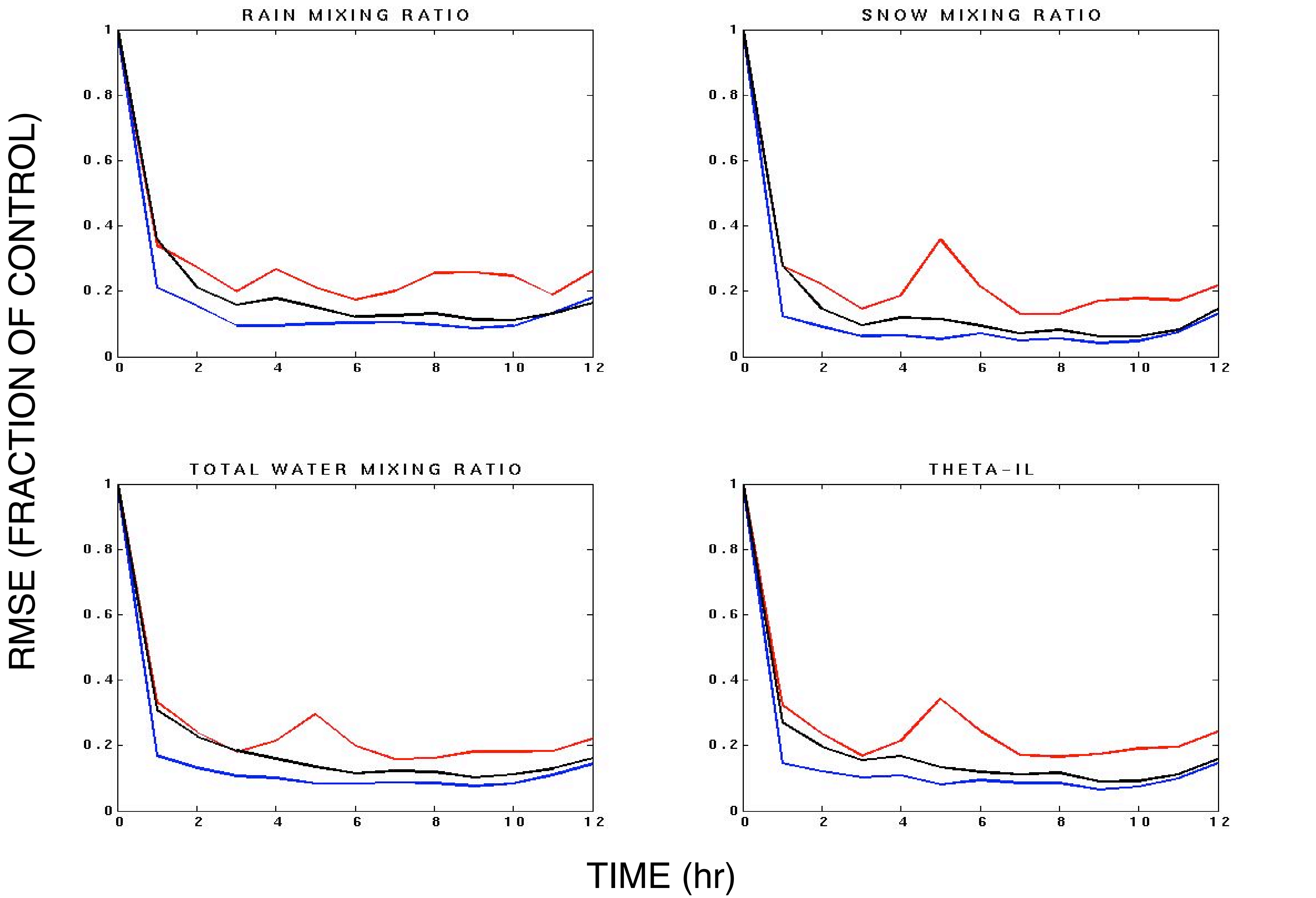
University of Wisconsin Nonhydrostatic Modeling System (UW-NMS) (Tripoli, 1992)

	Resolution	Gridpoints	IC, BC	m	Assimilation frequency
TR	95km / 15.8km 500m	85, 75, 35	GFS 60-km Analyses, OI SST	1	n/a
CTL	95km / 15.8km 500m	85, 75, 35	GFS 60-km 48-hr forecasts, OI SST	60	n/a
VR Z VRZ	95km / 15.8km 500m	85, 75, 35	GFS 60-km 48-hr forecasts, OI SST	60	V_r (1hr)$^{-1}$ Z (1hr)$^{-1}$ V_r and Z (1hr)$^{-1}$

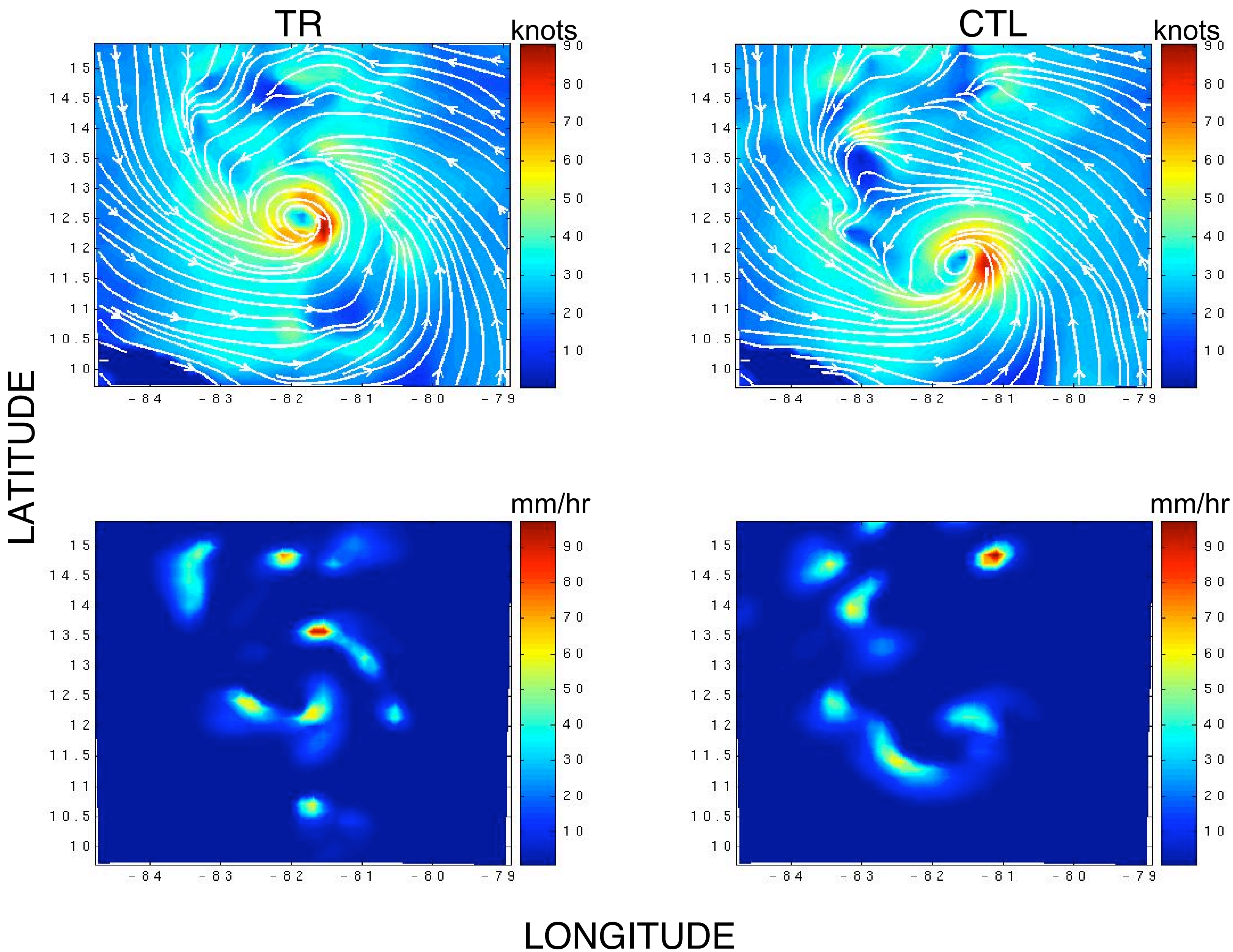
GRID-AVERAGED ERRORS FOR VR, Z AND VRZ



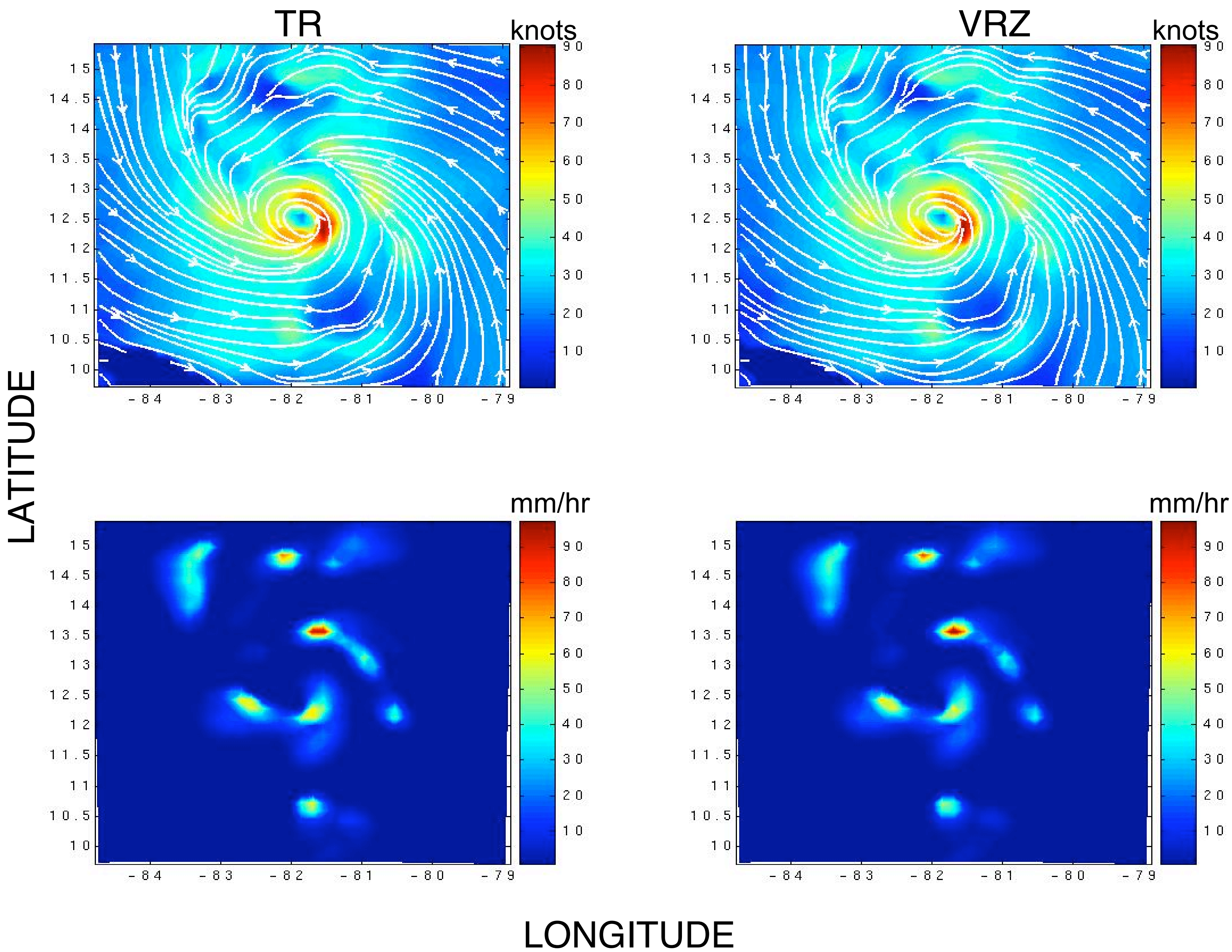
GRID-AVERAGED ERRORS FOR VR, Z AND VRZ



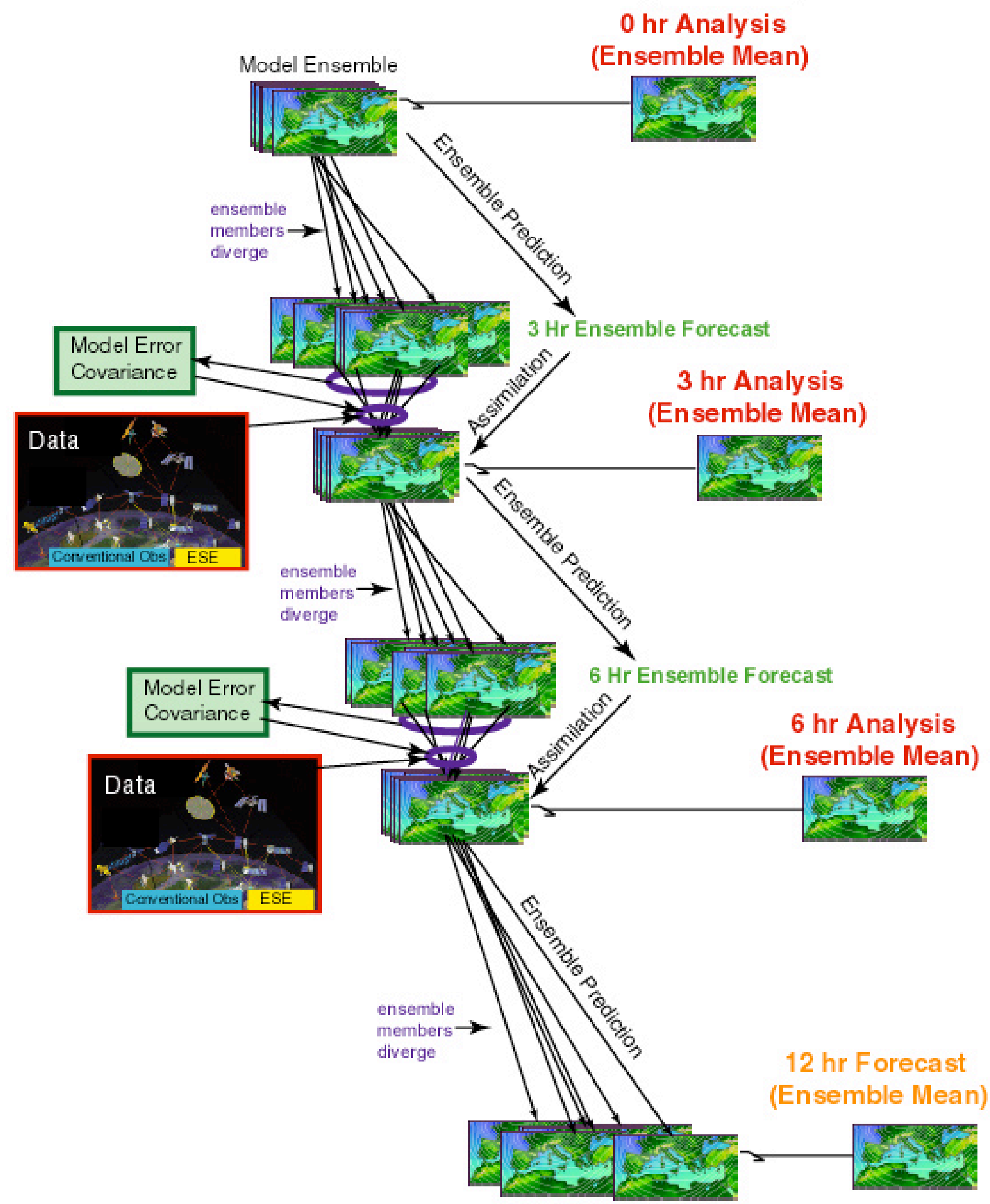
SURFACE WIND AND RAIN RATE FOR CTL, t = 12h



SURFACE WIND AND RAIN RATE FOR **VRZ**, t = 12h



Satellite Ensemble Analysis System



Summary

- As higher resolution cloud resolving weather analysis and model forecasts become possible, our approach to analysis must change to embrace probabilistic analysis and prediction
- GPM constellation approach fills a key void in the observations needed to drive a probabilistic CRM analysis and prediction system
- Current bulk microphysics models are not optimal for this future because of their inability to represent process faithfully
- AMPS and CRSDAS show promise as methodologies to advance the science and realize the potential of the GPM constellation

Future Research Plans

- **AMPS**
  - Further **refinement and validation of AMPS**
  - Develop **economical microphysics parametric approximations of AMPS** to reflect what we learn from AMPS about processes
- **CDRD** (Cloud dynamics and Radiation Database)
  - Implement AMPS technology
  - Study impact of tags on retrieval
- **CRSDAS**
  - Implement to ingest SSM/I , AMSR, CloudSat, and TRMM microwave and reflectivity together with GOES-IR for **limited area real time analysis and prediction of tropical cyclone genesis** in the central to eastern Atlantic basin